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# REVIEW ARTICLE

# Physics and Basic Parameters of Brachytherapy

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Brachytherapy (short-distance therapy) is the therapeutic process whereby radioactive sources are placed into very close proximity to target tissue. Radioactive materials were so used beginning shortly after the discovery of radium by Marie and Pierre Curie in 1898. For the purposes of brachytherapy, radioactive materials are those that emit ''rays'' that can cause ionization (and hence DNA damage and the destruction of target cells). The potentially useful rays include beta, gamma, and other possibilities such as neutrons. Beta rays, properly beta particles, are simply high energy electrons. Gamma rays are high energy photons (part of the electromagnetic spectrum like visible light, but with much higher energy). These particles are produced during the radioactive decay of certain isotopes. The physics of those events and the parameters that apply to the therapeutic use of the isotopes are the primary topics of this report.
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KEY WORDS: **physics; brachytherapy; radioactive; sources; implants; isotopes**

## INTRODUCTION

Brachytherapy is delivered by ''rays'' emitted by isotopes placed in close proximity to target tissue. The rays are the result of radioactive decay processes occurring within atomic nuclei. We briefly review fundamental nuclear physics, which describes such processes, and then relate the results to clinical applications.

There are four known forces in nature, ranging in strength as shown in Table I. The strong and weak nuclear forces and the electrostatic, or Coulomb, force are directly involved in radioactive decay processes. The gravitational force is not at all involved [1].

The atomic nucleus is in a state of conflicting forces: short range strong interactions bind all nucleons together, whereas Coulomb forces act to repel the like-charged protons making up a nucleus. As shown in Figure 1, within the very short range of the strong nuclear force, a ''well'' is created that ''traps'' the nucleons. Outside that well, the Coulomb repulsive force drives like-charged particles apart. The strength of this electrostatic force is given by $F = (-1/4\pi\epsilon_0)q_1q_2/r^2$ where the $q$s are the respective charges and $r$ is the distance between them. Since the strength depends inversely on the square of the distance separating the charges, the electrostatic force is sometimes called an inverse square force.

Although the exact process involved in the nuclear forces is not completely understood, some general patterns of behavior can be observed. For lighter elements with equal numbers of protons and neutrons, the strong interaction is overwhelming and the nucleus is generally stable, but as the number of nucleons increases within a nucleus, the Coulomb force may force the nucleons apart emitting particles and energy. These radioactive nuclei decay with statistical regularity and may be characterized in terms of their probability of decay and the type and energy of the emitted products. Such decays are independent of the isotopes' chemical or physical state.

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**TABLE I. The Four Fundamental Forces of Nature**

| Force | Relative strength |
|---|---|
| Strong nuclear | $10^{39}$ |
| Weak nuclear | $10^{13}$ |
| Electrostatic | $10^{2}$ |
| Gravitational | 1 |

The periodic table lists all elements in terms of increasing number of protons contained within the nucleus. Since unlike charges attract, there is a strong tendency for atoms to reach neutrality by having as many orbiting electrons (negatively charged) as nuclear protons (positively charged). As orbiting electrons are responsible for the chemical properties of different atoms, the periodic table is widely used in chemistry, listing each atom by increasing number of protons. In nuclear physics, however, the number of protons and neutrons within the nucleus determines the atom's behavior and so a new dimension has to be added to the table. The chart of the nuclides lists each element from hydrogen onward by increasing number of protons (represented by the letter *Z*), which determines the element's name, and by increasing number of neutrons (represented by the letter *N*), which separates each element into its isotopes. An example is shown in Figure 2. An isotope is either stable or radioactive. For those that are radioactive, the type of radioactive decay, the half-life, and the energy are often listed in the chart (not shown in our example).

Lighter elements containing similar numbers of neutrons and protons are generally stable; however, for atomic numbers above ~18, an increase in the number of neutrons to that of protons is required for stable isotopes. A general band of stability exists and can be represented as a curve on a chart of the number of neutrons, *N*, versus the number of protons, atomic number *Z*. This diagram is called a Segrè chart and is shown in Figure 3.

## RADIOACTIVE DECAY

The first radioisotope was discovered by Henri Becquerel in 1896 when he observed that uranium salts blackened photographic plates. In 1898, the Curies discovered two new radioactive elements, plutonium and radium. The latter they later purified from pitchblende into $Ra^{226}$, and this element was quickly used in medicine for the treatments of many ailments including cancer. In the early years, radium was in short supply and in great demand from hospitals throughout the world [2].

The decay product ''daughters'' of many isotopes further undergo decay until stable isotopes are reached. There may be many intermediate isotopes between the starting and stable isotopes. This sequential arrangement of decays is known as a decay series. There are three naturally occurring radioactive series, namely, uranium-radium, uranium-actinium, and thorium. Each series is named by its starting compound, which is long-lived compared to the age of the earth, hence its present existence. All of these series finally result in the formation of stable lead. $Ra^{226}$ is the sixth member of the series starting with $U^{226}$ and its long half-life of 1,622 years means it is relatively abundant. Some other isotopes in this series decay quickly and are therefore relatively less abundant.

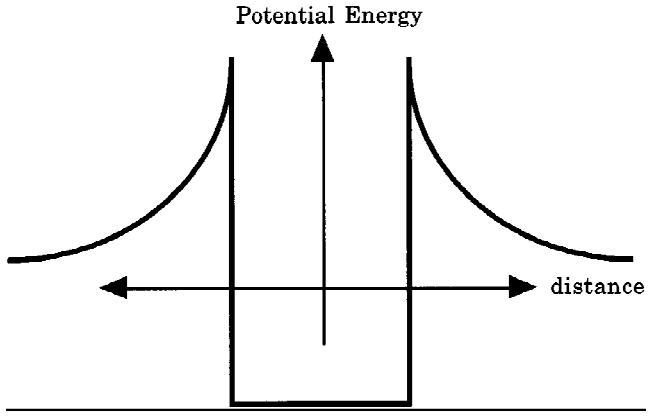


Fig. 1. A potential energy diagram of an atomic nucleus. The force holding the nucleus together, the strong nuclear force, creates the deep ''well'' from which nuclear particles have difficulty escaping.

Today there are >1,000 ''new'' artificially produced isotopes. By bombarding one element with various high-energy particles, it is possible to reconfigure the nucleus into a new arrangement that is often radioactive. For example, Iridium-192, $Ir^{192}$, is produced artificially by the neutron bombardment of $Ir^{191}$ or by the deuteron bombardment of $Os^{192}$ creating $Ir^{194}$, which then loses two neutrons to become $Ir^{192}$.

### Activity

Given a sample containing a large number of radioactive nuclei, the average rate of decay is proportional to the number of nuclei present. Thus $-dN/dt \propto N$ or $-dN =$ (constant) $\cdot N \cdot dt$, the minus sign represents a decrease in the number of atoms of the specific isotope during the time dt. Each radioactive isotope will have its own constant of proportionality, known as the decay constant, and given the symbol $\lambda$. Solution of this differential equation yields the exponential decay formula, $N = N_o e^{-\lambda t}$ where $N_0$ represents the number of nuclei at time $t = 0$. The half-life ($t_{1/2}$) of an isotope is defined as the time taken for the number of radioactive nuclei in question to be reduced to 1/2 of its initial value, i.e., for $N_0$ to be reduced to $N_0/2$. Substituting this in the above exponential equation, we obtain.

$$N = N_0 \cdot e^{-\lambda \cdot t} \quad \text{or} \quad \frac{1}{2} N_0 = N_0 \cdot e^{-\lambda \cdot t_{1/2}}$$

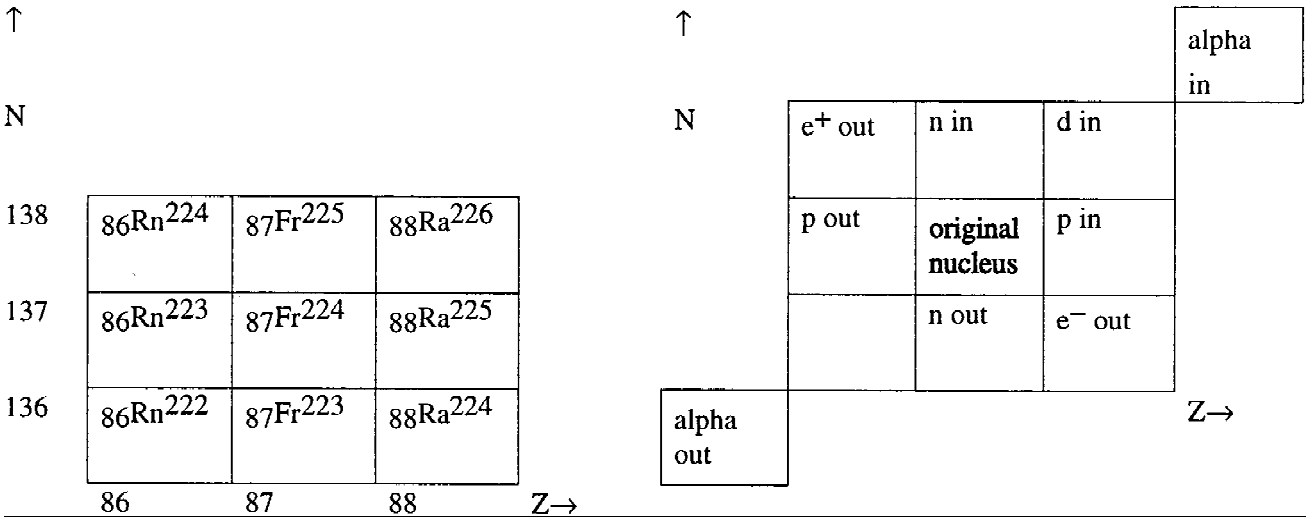


Fig. 2. A small portion of the chart of the nuclides. *N* represents the number of neutrons within a nuclide, *Z* represents the number of protons. The lefthand portion is of historical interest since the decay of $_{88}Ra^{226}$ to $_{86}Rn^{222}$ was utilized in the earliest brachytherapy. The righthand portion shows the mechanisms involved (relative to the original nucleus) in transitioning from one nuclide to another.

taking the natural log of both sides

$$\ln\left(\frac{1}{2}\right) = \ln\left(e^{-\lambda \cdot t_{1/2}}\right) \quad \text{or} \quad -0.693 = -\lambda \cdot t_{1/2}$$

thus giving the relationship between decay constant and half life

$$\lambda = {}^{0.693}\!/_{t_{1/2}}.$$

Substituting back into the exponential form, we obtain

$$N = N_0 \cdot e^{-\frac{0.693}{t_{1/2}} \cdot t}$$

After one half-life, 50% of the initial radioactive material remains, after two half-lives, 25% remains, after three, 12.5% remains, and so on. In general, the amount of material remaining after *x* half-lives is given by the equation: $N = N_0(1/2)^x$ (see Fig. 4).

As the activity, *A* (the number of decays per second), is directly proportional to *N* for a particular isotope; the above relation also can be written in terms of activity: $A = A_0e^{-\lambda t}$ where $A_0$ represents the activity at time $t = 0$.

Traditionally, activity was measured in Curies, Ci, where one Ci is equal to $3.7 \times 10^{10}$ disintegrations per second, dps, or in mCi where one mCi equals $3.7 \times 10^7$ dps. This number represents the activity of what was believed to be one gram, or milligram, respectively, of pure $Ra^{226}$. More accurate measurements show this number does not in fact represent one gram of pure radium, however, the numerical value of the Curie remains the same. Although the Curie is still a popular unit, the modern SI unit of activity is the Becquerel (Bq) where one Bq equals one disintegration per second. For isotopes that are useful in brachytherapy applications, the number of Bqs is very large so GBq is a more appropriate unit. One GBq unit equals $1 \times 10^9$ dps.

### Types of Radioactive Decay

Instability can manifest itself in any of several types of radioactive decay. The various types of decay were first observed in the late 1800s and early 1900s by Rutherford, Becquerel, Villard, Curie, and Joliot. The decay types were initially named according to the first three letters of the Greek alphabet, i.e., alpha (α), beta (β), and gamma (γ).

**Alpha decay.** Alpha decay, the emission of an alpha particle by a nucleus, is common among heavy isotopes and is described by reaction equations such as the following

$$_{88}Ra^{226} \rightarrow {}_{86}Rn^{222} + {}_{2}He^{4}.$$

The helium nucleus, $_2He^4$, is known as an alpha particle. Note in this example that the unstable nucleus $_{88}Ra^{226}$ has lost 2 protons and 4 mass units ($88 \rightarrow 86$ and $226 \rightarrow 222$). Also note that the α particle has exactly 2 protons and 4 mass units (2 protons + 2 neutrons). In this example, the α particle's energy is either 4.59 MeV (6% of the time) or 4.78 MeV (94%). This split is caused by the existence of two final energy levels in the $_{86}Rn^{226}$ nucleus. Each instance of the reaction branches to one or the other of the final energy levels. The branching ratio is predetermined by the characteristics of the parent and daughter nuclei. Finally, in tissue, α particles have a very

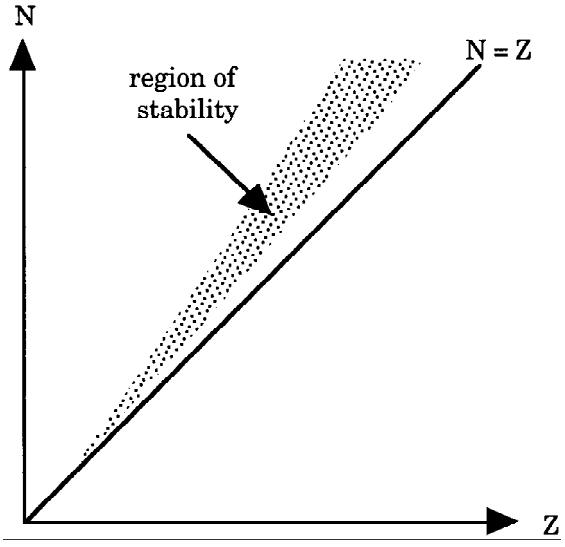


Fig. 3. Schematic ''Chart of the Nuclides.'' *N* represents the number of neutrons within a nucleus; *Z* represents the number of protons. The diagram shows that isotopes within the band of stability contain more neutrons than protons in their nuclei.

short range and considerable destructive power. They could be very hazardous if not properly contained. Clinical brachytherapy sources that contain alpha emitters are generally encapsulated such that the alpha particles are absorbed in the encapsulation shell and such that other, more clinically useful radiations can escape.

**Beta decay.** Beta decay is the emission of either a negatron (a negatively charged electron) or a positron (a positively charged electron, also known as an antielectron). Negatron decay occurs in neutron-rich nuclei when a neutron splits into an electron, proton and antineutrino. Neutrinos are essentially massless particles that do not significantly interact with matter. They are ignored from this point on. So, for the neutron split, we have

$$_0n^1 \rightarrow {}_{-1}\beta^0 + {}_1p^1 + \tilde{\nu}$$

where the negatron, $_{-1}\beta^0$, is immediately ejected from the nucleus (often written as $e^-$). The proton, $_1p^1$, stays within the nucleus. The anti-neutrino, $\tilde{\nu}$, is ejected. The ''~'' above the $\nu$ means ''antiparticle.'' An example of beta decay follows:

$$_{55}Cs^{137} \rightarrow (_{56}Ba^{137})^* + {}_{-1}\beta^0 + \tilde{\nu}.$$

The increase in atomic number ($55 \rightarrow 56$) is due to the formation of a proton from one of the neutrons. The total number of nucleons, however, remains constant at 137. The electron is the only particle ejected from the nucleus and its mass number is 0. In $\beta$ decay, the ejected electron's energy can range up to a well-defined maximum. For this example, $E_{max} = 0.51$ MeV (95% of the time)

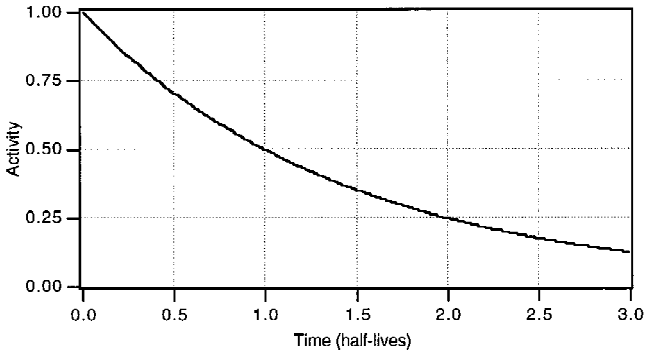


Fig. 4. An exponential decay curve representing the reduction in the radioactivity of a given sample with time.

and $E_{max} = 1.17$ MeV (5%). On average, ejected electrons have ⅓ of the maximum energy $E_{max}$. The * notation in the above equation indicates that the $Ba^{137}$ may be in an excited, i.e., metastable, state. This simply means that there is excess energy within the nucleus that may subsequently be ejected by the emission of a gamma ray.

**Gamma decay.** Gamma decay is the process whereby a packet of energy is ejected by a nucleus. That packet of energy is called a photon and also represents an electromagnetic wave. This dual nature (the wave particle duality) is summarized and simplified by a simple relationship between the energy of the particle and the frequency of the wave:

$$E = h \cdot \nu.$$

In this case, the Greek letter *nu*, $\nu$, represents the frequency of a wave (the number of wave cycles per second), *E* the energy of the photon (packet), and *h* Plank's constant ($h = 6.626 \times 10^{-34}$ J · s).

A nucleus that contains too much energy need not emit a ''solid'' particle. It gets rid of excess energy by ejecting an energy packet, a photon. Most decay events include more than one emission. An example is shown in Figure 5 in the form of a nuclear energy level diagram. The vertical axis represents energy and the horizontal atomic number. The ''straight'' arrows represent charged particle decay, whereas the oscillating arrows represent internal changes within the nucleus that result in the ejection of photons. This example also can be described by the reaction equation

$$_{27}Co^{60} \rightarrow {}_{28}Ni^{60} + \beta + \tilde{\nu} + \gamma.$$

An unstable $Co^{60}$ nucleus gets rid of excess energy when a neutron splits into a proton, electron, and antineutrino. The electron and antineutrino leave the nucleus. The nucleus now has one more proton (and one less neutron) than before, so *Z* goes up from 27 to 28 and chemically the atom has gone from cobalt to nickel. Now

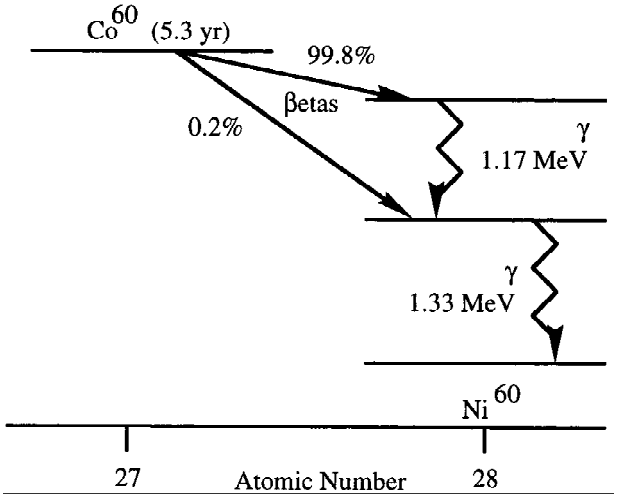


Fig. 5. A nuclear decay scheme diagram for radioactive cobalt-60 (the isotope with 27 protons and 33 neutrons having a half-life of 5.3 yr). Abbreviations for such isotopes are cobalt-60 or $_{27}Co^{60}$ or just $Co^{60}$. Note that within a $Co^{60}$ nucleus, an ''excess'' neutron splits into a proton (which stays in the nucleus), an electron (which is ejected), and a neutrino (ignorable). With the proton count increased, the nucleus is now $_{28}Ni^{60}$. The $Ni^{60}$ is initially in an excited state, but soon releases its excess energy by the emission of one or two gamma rays.

the nickel is created in an excited state (has too much energy), so it ejects one or two photons to get rid of that energy.

In Figure 5, we see that beta decay can lead to gamma decay. For $Co^{60}$, 99.8% of the beta decays leave the resulting $Ni^{60}$ in an excited state 2.5 MeV above ''ground'' level and 0.2% of the time in an excited state 1.33 MeV above ground. In either case, the excess energy is released as two or one gamma rays, respectively.

For most $\gamma$ decays, the photons are ejected very quickly after the initial decay, i.e., within $10^{-6}$ seconds. There are a few isotopes that have metastable energy states. If the nucleus arrives in one of these states, photon emission may not occur for hours. An example is $Tc^{99m}$ where the m indicates metastable.

**Positron decay.** Positron decay occurs when a proton within a nucleus splits into a neutron, positively charged electron (positron), and a neutrino.

$$_1p^1 \rightarrow {}_0n^1 + {}_{+1}\beta^0 + \nu$$

(The positron, $_{+1}\beta^0$, can also be written as $_{+1}e^0$). This event is more likely in neutron-poor nuclei as it ends up increasing neutron number while decreasing proton (atomic) number, i.e., shifts the balance toward stability (see Figure 3). For example,

$$_{15}P^{30} \rightarrow {}_{14}Si^{30} + {}_{+1}\beta^0 + \nu.$$

Atomic electron shells are labeled K, L, M, etc., from innermost to outermost. A very similar ''decay'' can

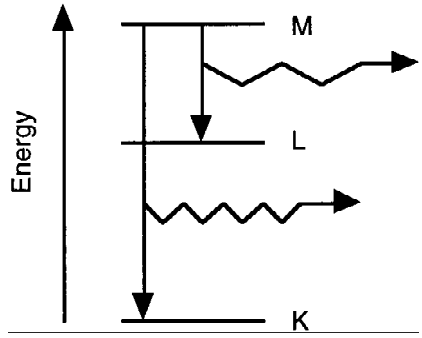


Fig. 6. K, L and M label the electron shells of an atom with the K shell being the innermost. With a K shell electron captured by the nucleus, the inner shell is left vacant. An electron cascade follows where electrons fall into the inner shells, releasing excess energy as characteristic X-rays.

eventuate when an inner shell, K, electron strays so close to the nucleus that electron capture occurs. The captured electron combines with a proton within the nucleus

$$_1p^1 + {}_{-1}e^0 \rightarrow {}_0n^1 + \nu.$$

Again, the atom's atomic number goes down while the neutron number goes up. When electron capture occurs, the resulting vacancy in the inner electron shell is filled by outer shell electrons cascading inward. This results in photon emission as the electrons move to lower energy orbits (states). An atomic (not nuclear) energy level diagram depicting such events is shown in Figure 6.

When an electron undergoes a transition to an inner orbit, i.e., the atom shifts to a lower energy state (schematically shown by a downward arrow), a photon is emitted of some characteristic energy (i.e., characteristic of that isotope). Also, since $E = h \cdot \nu = h \cdot c/\lambda$, a longer wavelength corresponds to a lower energy. Thus the larger energy transition (M shell to K shell in the diagram) produces a photon with a shorter wavelength (higher energy).

## CLINICAL APPLICATIONS

### Dose Specification

Because radium was the only available isotope for use in brachytherapy applications for many years, source strength was cited in milligrams (mg) and dose was prescribed in mg-hr (milligrams of radium times hours). A series of rules for implementation were developed starting in the 1930s relating the dose delivered to specific areas when certain arrangements of sources are used. These rules were often named after the place where they were developed, e.g., the Manchester and Paris [3].

With the introduction of other radioisotopes, the units of milligrams of radium had to be modified. One milligram of other isotopes does not have the same activity (strength) as one milligram of radium. Moreover, in gen-

**TABLE II. Some of the More Commonly Used Isotopes in Brachytherapy Applications**

| Isotope | Relevant energy (MeV) | Half-life | Exposure rate constant | Configuration |
|---|---|---|---|---|
| $Ra^{226}$ | 0.24–2.2 γ | 1622 y | 8.25 | sealed capsules or needles |
| $Rn^{222}$ | 0.78 γ | 3.83 d | 8.25 | sealed capsules |
| $Au^{198}$ | 0.42 max γ<br>0.96 β | 2.7 d | 2.38 | grains |
| $Ir^{192}$ | 0.3–0.612 γ<br>(0.37 ave.)<br>0.67 β | 74.2 d | 4.63 | seeds or wires |
| $Cs^{137}$ | 0.66 γ | 30 y | 3.2 | sealed capsules |
| $I^{125}$ | 0.028 γ | 60.2 d | 1.451 | seed |
| $Pd^{103}$ | 0.02 γ | 17 d | 1.48 | sealed capsules |
| $Sr^{90}$ | 0.546 β | 28.1 y | N/A | eye applicator |
| $Y^{90}$ | 1.74 γ<br>2.3 β | 64 h | N/A | rods |
| $Co^{60}$ | 1.25 γ | 5.26 y | 13.0 | sealed capsules |
| $P^{32}$ | 1.17 β | 14.3 d | N/A | liquid |
| $Ca^{252}$ | 1.0 n<br>0.5–1.0 γ | 2.6 y | N/A | sealed capsules |

eral, the same activity of two different isotopes will not deliver the same radiation dose at specific points from the source. To enable the use of new isotopes, namely, $Cs^{137}$ and later $Ir^{192}$, as replacements for radium, the unit milligram radium equivalent, mgRaEq, was developed. This unit gives the effective strength of an isotope in terms of the number of milligrams of radium that would deliver the same dose. Consequently, each isotope had a conversion factor allowing this comparison. The exposure rate constant, Γ, gives the exposure rate at one centimeter due to gamma rays from one mg of an isotope. For radium in its usual configuration, filtered by 0.5 mm of Pt, this factor is $8.25R \cdot cm^2/mCi \cdot hr$. Thus, 1 mg of radium (or by definition, 1 millicurie of radium) gives an exposure rate of 8.25R/hr at a point 1 cm from the source. In general, $dX/dt = A \cdot \Gamma/r^2$. Table II lists clinically used isotopes and their exposure rate constants.

Presently, the AAPM's recommendation is that the strength of brachytherapy sources be given in terms of air kerma strength, $S_K$, [4,5]

$$S_K = K(d) \cdot d^2$$

where K(d) is the air kerma rate at the calibration distance d and ''kerma'' means kinetic energy released in the medium [6]. The units of air kerma strength are

$$1\ U = 1\ \mu Gy\ m^2\ h^{-1} = 1\ cGy\ cm^2\ h^{-1}.$$

In rough analogy with the exposure rate constant, users of air kerma strength also must use the dose rate constant lambda, Λ. Lambda is defined as the dose rate to water at 1 cm from a source of strength 1 U. Λ is specified along the transverse axis of the actual source rather than from a point source [4]. In general, $D = \Lambda \cdot S_K$ at 1 cm. Note the dose rate falloff with distance is dependent on source size and will not fall off according to the inverse-square law. The air kerma strength is preferable over other methods of specifying activity because it does not require the use of gamma ray factors in its calculation. Over the years the exposure rate constants have been modified as measurements have been refined. Obviously, source calibrations and treatment plans must be computed using the same value of the exposure rate constant!

The unit of dose is the Gray, Gy, where 1 Gy = 1 J/kg. Typically, cGy are used as they are a direct replacement for the former unit of dose, the rad, and do not require subdividing (into decimals, i.e., one prescribes to the nearest integer cGy). Clinical effects due to brachytherapy sources are estimated by relating source strength (in mgRaEq or in air kerma strength) and placement time to dose deposition.

Today dose distribution calculations are accomplished by sophisticated computer programs that take as input source strengths, source locations, radiation anisotropy, and calculate accounting for attenuation (by encapsulation and by tissue), time, and tissue density. These programs make it possible to visualize complete distributions of the radiation patterns around even the most complex arrangement of radioactive sources. This very significant step forward has resulted in the demise of the use of dosimetry rules.

## Clinical Radioactive Sources

Clinically used sources have their radioactive material encapsulated to provide structure, protection, and filtering (of alpha, low energy beta, and low energy gamma). Without filtering, low energy beta particles could give rise to very high doses close to the surface of the source resulting in localized tissue damage. Radiation doses from Ra and Cs, e.g., arise solely from gamma rays. Radium sources are generally doubly encapsulated as the decay products include helium and radon gases, which over a span of years can build up significant pressure within the capsule.

Sometimes a localized dose may be desirable, e.g., in the treatment of superficial eye lesions. $Sr^{90}$ eye applicators take advantage of the decay of $Sr^{90}$ to $Y^{90}$. $Y^{90}$ emits high energy beta particles that are useful for very superficial treatments. The long-lasting $Sr^{90}$ (28 yr. half-life) regularly produces the shorter lived $Y^{90}$ (2–⅔ day half-life). The parent-daughter process reaches an equilibrium activity that provides for a long-lasting $Y^{90}$ source. A thin silver filter on one side of the applicators allows the beta particles to pass through the encapsulation, whereas a thicker backing on the other surfaces completely stops the beta rays.

## Brachytherapy Applications

Brachytherapy applications can be broadly divided into two types: those that are temporally placed and those where the sources are left in place permanently. Temporary implants involve leaving the isotope in position for a prescribed amount of time (normally ~1–4 days) to deliver the dose required and then removing them. For temporary implants, a long half-life source is normally desirable. There is a subdivision of temporary implants that use a very high activity source that is left in place for only a few seconds referred to as high dose rate (HDR) brachytherapy. Such applications require a specially shielded room and a remote device to position the source. Permanent implants leave the sources in position for the life of the patient or until subsequent surgical removal of the tumor with sources. Sources used for permanent implants, therefore, have to have relatively short half-lives.

## Dose Calculation Redux

If the isotope half-life is sufficiently long compared to implant duration, the activity of the source can be considered constant. Then the total dose delivered is simply the initial dose rate (cGy/hr) multiplied by the total time the sources are in place (hr). Sources most often used for temporary implants include $Cs^{137}$ ($t_{1/2}$ = 30 yrs) and $Ir^{192}$ ($t_{1/2}$ = 74.2 days). For permanent implants, the question of dose prescription becomes much more difficult. In addition to the many complex variables, one also has to consider that the dose rate is diminishing during the duration of the implant. The total dose given to the target will be that delivered in an infinite time. Practically this may be considered to be about five half-lives, by which time 97% of the dose will have been delivered. However, this may be an unacceptably long amount of time and the tumor response during the latter part of this time would be decreased as the dose rate is relatively low compared with its initial rate. The dose that is delivered during the first half-life may be more important than the same amount of dose that will be delivered in all subsequent half-lives combined, as the tumor response is dose dependent and may suffer a reciprocity law failure.

There are three common methods by which one prescribes the dose required for a permanent implant. The dose delivered in the first half-life alone, the dose delivered to total decay, and the dose delivered during the mean life of the isotope. Of these methods, the latter is probably the most popular, although it is important to specify what method should be used when prescribing the dose. The mean or average life of any isotope is defined as the time it would take for all of the radioactive atoms in question to decay if the material decayed at a constant rate equal to that of its initial activity. This hypothetical decay curve would appear, on a plot of activity versus time, as a horizontal line (constant activity) up until the time $t_{mean}$ when the curve would drop to zero activity. It can be shown that the so-called mean life is simply $t_{mean} = 1.44 \cdot t_{1/2}$ for all isotopes. The actual percentage of the isotope that will have decayed after this time is given by the integral of the true decay curve from $t = 0$ to $t = 1.44^* t_{1/2}$, or 63% decayed.

## HDR Brachytherapy

High dose rate brachytherapy has become increasingly popular over the last 10 years in the United States. In one system a single, very high activity $Ir^{192}$ source measuring ~4 mm long and 2 mm in diameter is laser welded into a cavity in the end of a long (150 cm), flexible braided wire. The source is housed inside a shielded safe within an afterloading machine that is capable of ejecting the active ''tip'' of the cable to desired distances with submillimeter accuracy. The small size of the source enables treatments not only within larger body cavities, such as the vagina and rectum, but also into much smaller lumens such as the bronchi and pancreatic ducts. In addition, rigid and flexible catheters can be placed through the tissues of many areas of the body enabling homogeneous doses to be delivered in a wide variety of sites. The treatment is given by placing the active source at various positions within each catheter for varying durations of time as determined by the treatment plan. The afterloading machine can place the source automatically for the desired duration and position in a catheter and then automatically move on to the next catheter in the sequence.

Although there are several advantages to treating with high dose rate brachytherapy, a possible disadvantage may arise from radiobiological considerations. Decades of clinical experience have lead to the belief that the advantages of brachytherapy were mainly twofold: close proximity resulting in high target dose and low surrounding tissue dose (geometric improvement), and protracted radiation exposure resulting in all phases of the cells' cycle being irradiated while permitting sublethal damage repair in normal tissue (biological improvement). Whereas the geometry can remain the same, the HDR dose is delivered almost instantaneously. Biologic studies predicted conversion regimes that required several repeat applications to mimic the LDR tumor and normal tissue responses.

There is another disadvantage with HDR units that must be considered: the consequence of machine malfunction may be severe for both patient and operating personnel. Extraordinary care is taken to assure that a source will be returned to its shielded position in the center of the safe if any problems are experienced by the machine. The operating design of the units contain redundant checks and backup systems to ensure safety. Strict operating procedures involving redundant safety checks are mandated to limit the likelihood of a radiation incident requiring the manual removal of the source.

Emergency procedures have to be in place to allow rapid response to this situation should it occur. Unfortunately, poor procedures, equipment failure, and inattentiveness have lead to some serious mistakes in the past [7].

The clear advantages of HDR result from the short treatment duration. Brachytherapy sources are never left unattended. The patient is not ''hot'' between fractions and thus may have unrestricted visits and nursing care and may even be sent home between treatment fractions. The catheters or applicators are unlikely to shift during the short exposure times of the treatment. The treatment may be given intraoperatively during surgical procedures. Normal tissues can sometimes be moved away from the source during the treatment. There is no exposure to hospital personnel. Hospital stay is often reduced or completely eliminated. Radiation patterns can be improved by optimizing the source dwell time, effectively giving an infinite library of source activities.

Presently there is great interest in expanding the use of high dose rate treatments to include intravascular irradiations for the prevention of neointimal hyperplasia following vascular or arterial damage (as occurs in coronary angioplasty or peripheral vascular shunting). New beta emitting brachytherapy sources are being proposed for this purpose. Oncologic uses of intravascular applications also may prove valuable for inoperable lesions that adhere to blood vessels.

### Radiation Precautions

The preparation and manual loading of brachytherapy sources can result in substantial doses being received by hospital personnel. Specific limits addressing the amount of occupational radiation one may receive are mandated by the Nuclear Regulatory Commission. Institutions are responsible for implementing processes to assure that exposures are not only within regulatory limits, but also as low as reasonably achievable (ALARA). Staff and patient education is crucial to an ALARA program. For those who must handle radioactive materials, three general considerations should be employed: minimize exposure time, maximize distance to the sources, and utilizing appropriate shielding whenever possible.

## CONCLUSIONS

The basic physics and parameters of modern brachytherapy are no different from those employed by our predecessors. Technology has, however, enabled us better to apply radioactive sources resulting in more homogeneous and reproducible doses. More accurate calculations of normal tissue and tolerance tissue doses have allowed increases in the dose given to the target tissue. The resulting more customized applications should provide improved treatment outcomes for our patients.

## REFERENCES

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